# The Flow and Fracture of Cracked Ice: Experiments to Aid Modeling

Erland M. Schulson
Thayer School of Engineering, Dartmouth College
8000 Cummings Hall
Hanover, NH 03755-8000
phone: (603) 646-2888 fax: (603) 646-3856 email: erland.schulson@dartmouth.edu

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## LONG-TERM GOALS

My ultimate goal in this work is to contribute new physical insight to the development of next generation sea ice model, "PIPS 3.0". More specifically, I wish to understand the processes underlying the formation of oriented leads in sheets of first-year sea ice.

## OBJECTIVES

I wish to establish whether the leads that form within an anisotropic ice cover at high-latitudes develop from the growth and interaction under far-field compression of pre-existing flaws, such as thermal cracks and re-frozen leads. With this in mind, my near-term objectives are to study and understand the mechanical behavior of columnar sea ice under controlled conditions and to determine the role played by pre-existing flaws. I plan to study the compressive failure pattern on scales accessible to controlled experiments, and then to compare these patterns to those seen on satellite images.

## APPROACH

Deformation experiments on both the laboratory (sub-meter) and the intermediate/engineering (meter) scales are underway. A study is being made of the mechanical behavior of meter-sized blocks of ice grown under natural conditions and of the behavior of smaller specimens harvested from the larger blocks. The material is characterized by columnar grains whose crystallographic c-axes are randomly oriented within the plane of the sheet, as in natural first-year sea ice covers. The blocks are designed to contain an array of pre-existing crack-like flaws, and are being loaded under compression at controlled strain rates. The experiments are being performed using a novel loading frame installed outdoors in a pond at USA-CRREL.

## WORK COMPLETED

The first set of experiments using the outdoor facility was completed during the winter of '98. Weather conditions cooperated, but not to the degree that is needed for long-term study: temperatures hovered around freezing. Nevertheless, the preliminary work allowed the facility to be "de-bugged" and a set of results from meter-sized blocks to be obtained for comparison with results obtained in the laboratory from smaller specimens.

Experiments in the laboratory on smaller specimens have exposed what we believe is the trigger that activates compressive shear faults. The failure pattern seen there is very much like the pattern seen on

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satellite images of natural sea ice covers, suggesting a scale-invariance to the fundamental physics of compressive failure.

In the interests of further exploring the validity of Hill's failure criterion for saline ice, preliminary lab tests have been completed on the compressive failure under triaxial loading of blocks of ice whose columnar axes are neither parallel nor perpendicular to the applied stresses.

## RESULTS

Fourteen experiments were performed on 0.16 m thick blocks one meter on edge loaded under uniaxial compression at strain rates from $10^{-5}$ $s^{-1}$ to $10^{-2}$ $s^{-1}$ at temperatures close to the melting point. The experiments showed that the ductile-brittle transition occurred at a strain rate of $10^{-3}$ $s^{-1}$; i.e., at the same rate at which smaller specimens undergo the transition. Analysis of the ductile compressive strengths showed strain rate sensitivity m=0.23 ($\sigma \propto \varepsilon^m$), in agreement with values obtained from smaller specimens obtained from the lab (Kuehn and Schulson, 1994) and from the field (Timco and Frederking, 1986). The preliminary results provide *no evidence for an effect of size* on the ductile compressive behavior of saline ice, at least over the order of magnitude (linear dimension) range examined here.

Concerning brittle compressive failure, direct observations have established the micromechanical events leading to the development of a shear fault. During loading, wing cracks develop at the tips of sliding parent cracks and tend to align with the maximum principal stress. Sets of closely spaced splay cracks emanate from one side of the parent sliding crack, and play the dominant role in activating the fault. The central idea is that the slender columns between the splay cracks are more likely to buckle and fail than are the columns between adjacent wing cracks because they do not have two fixed ends; instead, the end stemming from the inclined parent crack is free. A moment is then applied by frictional sliding of the parent inclined crack and this causes the fixed-free columns to break at a much lower stress than the fixed-fixed columns. Columns created near a free surface are more likely to fail than those created elsewhere, and this explains the observation that shear localization tends to initiate near free surfaces. A first-order calculation shows that the failure stress of the splay-created columns is of the same order of magnitude as the terminal failure stress. At the time of writing a paper, entitled "On the initiation of shear faults during brittle compressive failure: A new mechanism", by E.M. Schulson, D. Iliescu and C.E. Renshaw, is in press in JGR–Solid Earth. Noted is the striking similarity in the lab-scale failure pattern with that seen from satellite images of the Arctic ice cover (Richter-Menge et al. 1996), suggesting that physics of faulting is scale independent. Leads, in other words, are probably giant compressive shear faults.

Finally, loading columnar ice off axis appears to activate grain boundary sliding during the early stages of deformation, but not to require major revisions in the failure criterion established by Melton and Schulson (1998). Hill's criterion, in other words, appears to still describe the ductile failure stress. Analysis is continuing using other criteria for comparison.

## IMPACT/APPLICATIONS

As noted in PR97, the results are beginning to impact the development of the numerical modeling of the flow and fracture of anisotropic sea ice and of lead formation. I have collaborated/am collaborating with Bill Hibler on this matter. Together we have published one Annals of Glaciology paper and have another paper in press in JGR (see list below). Although it is too soon to tell, the new mechanism of shear faulting has the potential to impact not just ice mechanics but also tectonophysics.

**TRANSITIONS**

As noted above, the conceptual results of my work are being utilized by Bill Hibler in his modeling the formation of leads.

**RELATED PROJECTS**

Closely related to this project is one by Bill Hibler under a separate ONR grant N00014-97-1-0381. He is numerically modeling the fracture and flow of anisotropic (cracked) sea ice. Pre-existing flaws have a major effect on the pattern seen, as does the applied stress state. These points will be investigated at the intermediate scale during our next series of outdoor tests.

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